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Sequential Analysis of Automatic Target Detection with Classification Algorithms and Optimality of Dynamic Decision Making Under Uncertainty

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The Regents of the University of Michigan

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14. ABSTRACT

Applied novel mathematical techniques to a published data-set (Roitman and Shadlen, 2002) on LIP neuronal activities during a random-dot motion discrimination paradigm to identify/classify individual neurons in terms of their sensori-motor locus and the putative "decisional" process that translates a perceptual to a motor representation. Developed a Signal-Detection-Theory based analysis providing a quantitative measure of sensorimotor locus of the neuron at each time point, and a Poisson regression model incorporating orthogonal decomposition of neuronal activity in term of how the stimulus, response, and stimulus-response mapping components contribute to the spike activity. Developed techniques to extract S-, R-, or SR mapping components in neural recordings of time series, e.g. event-related potentials (ERPs) where trial-by-trial variations in response-time have contaminated their contributions in averaged waveforms. Modeled motivational impact ("incentive salience") in reinforcement learning, a standard paradigm for sequential decision making. Empirically investigated, through perspective taking manipulation, depth of recursion in st

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AFOSR Project (FA9550-06-1-0298)

Sequential Analysis of Automatic Target Detection with Classification Algorithms and Optimality of Dynamic Decision-Making Under Time Pressure

PI: Jun Zhang (University of Michigan)

Final Report

The above-referenced project commenced on May 1 2006, with project termination date initially set as April 30 2009, and total cost of $336638 (including indirect cost). On May 7 2007, a one-time supplement fund of $75000 was awarded. On Oct 8 2007, upon the request of the University of Michigan, PI was changed to Prof. William Gehring of the Department of Psychology, University of Michigan. On April 9, 2011, upon the request of the University of Michigan, PI was change back to Prof. Jun Zhang, the original PI. No-cost-extension (NCE) applications were filed and were approved so that grant termination date was eventually set to March 30 2012. The project concluded as of March 30 2012.

The project was about dynamic decision-making under time pressure, when one is faced with the tradeoff between the benefit of improving decision accuracy associated with continued observation of the environment and the cost for making additional observations and/or for delaying a decision. The modeling framework adopted was Bayesian sequential analysis, with random-walk/drift-diffusion for evidence accumulation process, and optimal combination of bottom-up evidence accumulation (likelihood function) with top-down contextual knowledge (prior expectation) as the stream of data flows in. Such analysis were to apply to Automatic Target Recognition (ATR) systems which acquire a sequence of images are where potential targets (aircraft, tank, etc) are embedded but not immediately and/or obviously detectable. The project was a collaboration between the PI at the University of Michigan and Dr. Daniel Repperger at AFRL Wright-Patterson Air Force Base.

During the execution of the project, two unexpected events occurred that have significant impacted the original plan. First, the original PI, Dr. Jun Zhang, has been on an IPA assignment to AFOSR from Sept 1, 2007, initially for two years but later extended until Jan 10 of 2011. He relocated to Arlington VA and served as the Program Manager of the Mathematical Modeling of Cognition and Decision Program at the Directorate of Mathematics, Information and Life Sciences. During his absence from the University of Michigan, Dr. Gehring served as the Project Director while Dr. Zhang (while not deriving any salary or fringe benefits from the grant) maintained

his supervision of students for carrying out research activities under this project. Secondly, Dr. Repperger of AFRL suffered from a heart attack and died on Jan 10, 2010. The untimely passing of Dr. Repperger, an AFRL Fellow, was a tremendous loss to the Lab and negatively impacted the project, as the ATL portion of the project was a collaborative effort.

Despite of these adverse events, we were still able to make significant progress in the following four areas for understanding decision making and its neural mechanisms: 1) the analysis of event-related potential (ERP) components related to stimulus, response, and the decision process that link the two; 2) the analysis of neuronal activities related to decision making; 3) the modeling of motivational force ("incentive salience") for decision making; 4) strategic reasoning and decision making in games. A detailed report of research findings will be given below.

Publications supported (or partially supported) by the grant:

1. Wei, H., Zhang, J., Cousseau, F., Ozeki, T., and Amari, S. (2007). Dynamics of learning near singularities in layered network. *Neural Computation*, **20**, 813-843.

2. Berridge, K., Zhang, J., and Aldridge, W. (2008). Computer motivation: Incentive salience boosts of drug or appetite states. *Behavioral Brain Science* **31**:440-441.

3. Chavez A, and Zhang J. (2008) Metagame strategies of nation-states, with application to Cross-Strait relations. In H Liu, J Sereno and M Young (Eds), *Proceedings of the First International Workshop on Social Computing, Behavioral Modeling, and Prediction* (SBP2008), Springer.

4. Zhang, J. Tindell, A.J., Berridge, K.C., Zhang, J., and Aldridge, J.W. (2009). Modeling the neural computation of incentive salience. *PLoS Computational Biology*, **5:** 1-14.

5. Stern, E., Liu, Y., Gehring, W., Lister, J., Yin, G., Zhang, J., Fitzgerald, K., Himle, J., Abelson, J., Taylor, S. (2010). Chronic medication does not affect hyperactive error responses in obsessive-compulsive disorder. *Psychophysiology* **47**: 913-920.

6. Yin, G., Zhang, J., Tian, Y. and Yao, D-Z. (2009). A multi-component decomposition algorithm for event-related potentials. *Journal of Neuroscience Methods*, **178**: 219-227.

7. Park J & Zhang J (2010). Sensorimotor locus of the buildup activity in monkey lateral intraparietal area neurons. *Journal of Neurophysiology*. **103**: 2664-74.

8. Zhang, J., Berridge, K., Tindell, A., and Aldridge, J.A. (2011). Computational models of incentive-sensitization in addiction: Dynamic limbic transformation of learning into motivation. In Gutkin, B. and Ahmed, S.H. (Eds.) *Computational Neuroscience of Drug Addition.* Springer (pp.189-203).

9. Zhang, J. (2011). Model selection with informative normalized maximum likelihood: Data prior and model prior. In Dzhafarov, E.N and Perry, L. (Eds) *Descriptive and Normative Approaches to Human Behavior.* World Scientific, New Jersey (pp. 303-319).

10. Yin, G and Zhang J (2011). On decomposing stimulus and response waveforms in event-related potentials. *IEEE Transactions on Biomedical Engineering*, **58:** 1534-1545.

11. Zhang, J., Hedden, T and Chia, A. (2012) Perspective-taking and depth of theory of mind reasoning in sequential-move matrix games. *Cognitive Science,* **36:** 560-573.

12 . Zhang, J. and Yin, G. (in press) A method to decompose stimulus and response components in event-related potential (ERP) recordings (book chapter to appear).

Students supported on the grant:

1. Alex Chavez, Ph.D. in Psychology completed 2010.
2. Yin Gang (exchange student), Ph.D. completed 2010.
3. Joonhoo Park, Ph.D. in Psychology completed 2011.
4. Haizhang Zhang, Postdoc completed 2011. Now Professor of Mathematics at Sun Yat-Sen University, China.
5. Ajinkya More, Ph.D. in Mathematics completed 2011.

Summary of Research Findings:

There have been four main areas of research that were conducted under the support of this grant.

1) Decomposing ERP components related to stimulus, response and the decision that links the two (Publication #5, #6, #10, #12)

Event-related potentials (ERPs) reflect the brain activities related to specific behavioral events, and are obtained by averaging across many trial repetitions with individual trials aligned to the onset of a specific event, e.g., the onset of stimulus (s-aligned) or the onset of the behavioral response (r-aligned). Examples of the former included P300 and N400 components, and examples of the latter include error-related negativity (ERN) and lateralized readiness potential (LRP). However, the s-aligned and r-aligned ERP waveforms do not purely reflect, respectively, underlying stimulus (S-) or response (R-) component waveform, due to their cross-contaminations in the recorded ERP waveforms. Earlier, Zhang [J. Neurosci. Methods, 80, pp. 49–63, 1998] proposed an algorithm to recover the pure S-component wave- form and the pure R-component waveform from the s-aligned and

r-aligned ERP average waveforms—however, due to the nature of this inverse problem, a direct solution is sensitive to noise that dis- proportionally affects low-frequency components, hindering the practical implementation of this algorithm. During the grant period, working with an exchange student Gang Yin, we apply the Wiener deconvolution technique to deal with noise in input data, and investigate a Tikhonov regularization approach to obtain a stable solution that is robust against variances in the sampling of reaction-time distribution (when number of trials is low). This method is demonstrated using data from a Go/NoGo experiment about image classification and recognition.

Our method was applied to a study of patients with obsessive-compulsive disorder (OCD) about whom the literature said there was an increased error-related negativity (ERN). In that study, with medication use properly controlled, we found greater ERNs in OCD patients than in controls, irrespective of medication use, suggesting that elevated error signals in OCD may be disorder-specific.

Finally, we were able to extend our analytic tools to deal with three or more markers in a single trial, and recover individual ERP components that are time-locked to those markers. As an application, we analyzed a cuing experiment with three events: cue, stimulus and response. The elapse between cue and stimulus was varied from trial to trial by the experimenter, and the time between stimulus and response was determined by the subjects (reaction-time variation). Our decomposition results show that the cue- dependent component waveform turns out to flatten out 500ms after cue-onset, a finding consistent with our experimental paradigm.

The suite of methods we developed under the grant support actually addresses and solves a problem when other traditional methods may fail (i.e., when event time distributions are large), so it is a completely complementary technique in ERP multi-component analysis. Though our simulations are based on ERP context, the basic mathematical technique behind our method can also be easily adapted to deal with event-related signals in other neuro-imaging studies (e.g. fMRI), such that trial-by-trial variation in behavioral reaction time is no longer an obstacle but rather an opportunity for isolating the underlying neurocognitive processes mediating a task.

2) Analyzing neuronal activity related to perceptual decision making (Publication #7)

Random-walk/drift-diffusion models have in recent years been used to model neural basis for decision making. Neurophysiological data provided support that neurons in certain brain areas (such as MT and LIP) were responsible for the perceptual decision of an animal (monkey) in visual discrimination task. However, the exact role of each individual recorded neuron, namely sensory, motor, or sensorimotor transformation ("decision" to translate from sensory representation to motor representation) is completely clear. In our study performed under the grant, we applied novel mathematical techniques to analyze a published dataset,

published in 2002 by Roitman and Shadlen, who showed in a random-dot motion-discrimination paradigm showed that information accumulation model with a threshold-crossing mechanism can account for activity of the lateral intraparietal area (LIP) neurons. Our specific question was to quantitatively address the sensory versus motor representation of the neuronal activity during the time course of a trial. A technique based on Signal Detection Theory was applied to provide indices to quantify how neuronal firing activity is responsible for encoding the stimulus or selecting the response at the behavioral level. Additionally, a statistical model based on Poisson regression was used to provide an orthogonal decomposition of the neural activity into stimulus, response, and stimulus-response mapping components. The temporal dynamics of the sensorimotor locus of the LIP activity indicated that there is no stimulus-response mapping-specific neuronal firing activity throughout a trial; the neural activity toward the saccadic onset reflects the development of the motor representation, and the neural activity in the beginning of a trial contains little, if any, information about the sensory representation. Sensorimotor analysis on individual neurons also showed that the neuronal activation, as a population, represent pending saccadic direction and carry little information about the direction of the motion stimulus.

Our technical innovation allowed us to analyze the information accumulation process in the LIP activity and examined the sensorimotor nature of the representation of information encoded by recorded neurons on a trial-by-trial basis. Our SDT-based analysis provides a quantitative measure of sensorimotor locus of the neuron at each time point, and the Poisson regression model incorporating orthogonal decomposition of neuronal activity provides a quantitative assessment as to how the stimulus, response, and stimulus-response mapping components contribute to the spike activity.

3) Modeling motivational effects or "incentive salience" in decision making
(Publication #2, #4, #8)

Motivational impact on decision making has been widely modeled using reinforcement learning paradigm. Incentive salience is a motivational magnet property attributed to reward predicting conditioned stimuli (cues). This property makes the cue and its associated unconditioned reward 'wanted' at that moment, and pulls an individual's behavior towards those stimuli. The incentive-sensitization theory of K. Berridge and T. Robinson, which was initially proposed in the drug addiction context, posits that permanent changes in brain mesolimbic systems in drug addicts can amplify the incentive salience of Pavlovian drug cues to produce excessive "wanting" to take drugs. Collaborating with Berridge and colleagues, we built a computational model of incentive salience to captures motivational impact on reward learning, and contrast it to traditional cache-based models of reinforcement learning. Our motivation-based model incorporates dynamically modulated physiological brain states that change the ability of cues to elicit "wanting" on the fly. These presumed brain states include the presence of a drug of

abuse and longer-term mesolimbic sensitization, both of which boost mesocorticolimbic cue-triggered signals. We have tested our model using recorded neuronal activity from mesolimbic output signals for reward and Pavlovian cues in the ventral pallidum (VP), and a novel technique for analyzing neuronal firing "profile", presents evidence in support of our dynamic motivational account of incentive salience.

4) *Modeling and empirical study of strategic reasoning for decision making in games* (Publication #3 and #11)

Strategic interpersonal interaction, as modeled by mathematical game theory, involves rational players weighing their choice of actions through analyzing player-specific payoffs associated with outcomes that are jointly determined by their own and their opponents' choices (Von Neumann & Morgenstern, 1944; Luce & Raiffa, 1957). This is decision making under uncertainty in social domain. Traditional game theoretic approaches assume that players take full advantage of common knowledge and rationality (CKR) in games of complete information (Binmore, 1992; Osborne & Rubinstein, 1994). Common knowledge is said to exist when all players know something to be true, know that all players know it to be true, know that all players know all players know it to be true, and so on. Normative (equilibria) solutions of games require recursive modeling of other players to its full depth, leading to the framework of epistemic game theory (Mertens & Zamir, 1985; Brandenburger & Dekel, 1993). Such recursive modeling is manifested in developmental psychology as the so-called "Theory-of-Mind" (ToM) reasoning. In this study, we manipulated participants' perspectives in games in order to differentiate ToM-based recursive reasoning from the confounding factor of decision horizon in look-ahead planning or backward induction in multistage games.

In a two-person, three-stage board game we designed, players take turns in controlling the progression or termination of the game (from Cell A to B and to C). In predicting Player II's optimal choice at Cell B, participants adopt a first-person perspective (1PP, "planning") when assigned the role of Player II, or a third-person perspective (3PP, "anticipation") when assigned the role of Player I. The need for sequential planning is equivalent for both assignments—the payoff comparisons involved are formally identical and require the same working memory load. However, we showed a clear advantage for 1PP over 3PP in achieving predictive reasoning (i.e., in considering Player I's countermove upon arriving in Cell C). Although most participants in 1PP and 3PP began with a myopic ToM strategy, those in 1PP were more likely to eventually acquire predictive ToM reasoning. Participants in 3PP are placed farther up in the analysis stream (compared with 1PP), with the corresponding disadvantage of having to process one more level of ToM recursion. This suggests that we are more ready to anticipate others' reactions to an action we plan than to accommodate that others, when planning their action, may have already taken into account possible counter-reactions from ourselves. Our study delineated "instrumental rationality" in decision making (the

ability to rationally choose optimal actions given a belief–desire state) from "inductive rationality" (the ability to establish the most predictive model of the opponent) in strategic reasoning.

In a separate study, we applied such recursive ToM reasoning ("I think you think I think . . . ") to normative solution to games, known as the meta-game analysis (Howard, 1968). The case is an international political dispute involving Taiwan Strait. The Cross-Strait relations were modeled as a three-person game, with Taiwan, China, and the U.S. as players. Preferences of these nation-states over various outcomes were given as the starting point, and equilibria of meta-game strategies were meta-game outcome were derived.